

**Comprehensive Analysis of P and S Spectra
from Southern California Earthquakes**

Award 07HQGR0095

Peter M. Shearer
Institute of Geophysics and Planetary Physics
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, CA 92093
858-534-2260 (phone), 858-534-5332 (fax)
pshearer@ucsd.edu

Program Element: III

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 07HQGR0095. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

Award 07HQGR0095

Peter M. Shearer
Institute of Geophysics and Planetary Physics
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, CA 92093
858-534-2260 (phone), 858-534-5332 (fax)
pshearer@ucsd.edu

TECHNICAL ABSTRACT

Permanent and portable seismic networks in southern California record a tremendous volume of broadband waveform data from local earthquakes. We propose to continue using a newly created online database of southern California seismograms to systematically compute, store, and analyze *P* and *S* spectra from the over 300,000 events recorded since 1984. Our analyses of the spectra will help address the following issues: (1) Do earthquake source spectra scale such that apparent stress is constant with respect to event size? (2) Do earthquake stress drops in southern California vary systematically in space and time? Can variations in earthquake stress drop be related to changes in the stress field caused by large ruptures? (3) What is the three-dimensional attenuation structure beneath southern California? (4) Can directivity effects be routinely observed in earthquake source spectra? (5) Can *P* and *S* amplitude information help improve earthquake focal mechanism accuracy compared to *P* polarity information alone? Anticipated results of this work include a more detailed understanding of earthquake source properties and new maps of lateral variations in crustal attenuation structure. This knowledge will contribute to quantitative assessments of earthquake potential and seismic hazard in southern California.

Award 07HQGR0095

Peter M. Shearer
Institute of Geophysics and Planetary Physics
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, CA 92093
858-534-2260 (phone), 858-534-5332 (fax)
pshearer@ucsd.edu

NON-TECHNICAL ABSTRACT

We are developing automated processing techniques to provide a practical way to examine the large seismic data bases collected from permanent and portable networks in southern California. Our recent building of a complete online waveform database for this region makes possible much more comprehensive computation and analysis of earthquake source spectra than has previously been achieved. Analyses of these spectra will directly address a number of issues related to seismic hazard. These include questions concerning:

- (1) Earthquake scaling: can the shaking expected from large earthquakes be predicted from that observed much more commonly in small earthquakes?
- (2) Crustal stress: Are there variations in stress drops of small earthquakes that can be used to characterize stress field heterogeneity and identify regions of stress concentration?
- (3) Subsurface fault orientation: can the geometries of small earthquake faults be resolved through observations of rupture directivity effects?
- (4) Attenuation structure: how might ground shaking from future events be affected by differences in the energy loss during wave propagation?

In the long run, our results will provide basic knowledge about source processes and seismic wave propagation that will increase the ability of seismologists to make realistic forecasts regarding strong motion probabilities in different locations, thus contributing to the NEHRP goal of reducing losses from earthquakes in the United States.

Results

We have now computed spectra from over 400,000 events, from 1981 to the present. Our results are expanded compared to those analyzed in Shearer et al. (2006) in that we examine 6 more years of data, including many more of the broadband TriNet records. Our procedure involves selecting windows around both the *P* and *S* waves, using the operator phase picks, if available, or applying an automatic picking algorithm. Spectra are computed using a multitaper method on all available channels and components, including rotation into transverse and radial components. Spectra are also computed from pre-arrival noise windows in order to estimate signal-to-noise ratios. We store the spectra in a special binary format designed for rapid storage and retrieval of the millions of spectra we obtain. Our spectral database currently requires about 100 Gbytes of storage on a RAID system at Caltech.

Following application of a signal-to-noise cutoff criteria and corrections for the known gain and instrument response, we process the spectra in ways that isolate source, receiver and propagation path effects. This is an important step because individual spectra tend to be noisy and irregular in shape and difficult to fit robustly with theoretical models. However, by stacking thousands of spectra it is possible to obtain much more consistent results.

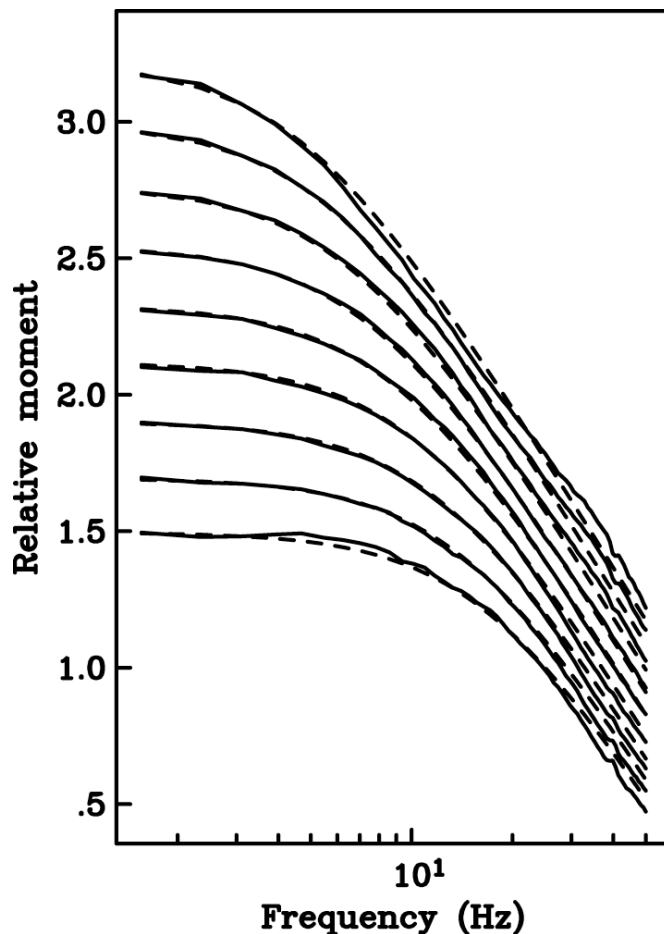


Figure 1. Source displacement spectra stacked within bins of equal log moment (solid lines) compared to the fit obtained using a constant stress drop model of $\Delta\sigma = 1.6$ MPa (dashed lines). Observed spectra are corrected using an EGF method. The fit degrades beyond 20 Hz because of signal-to-noise limitations in the data.

Our initial analysis of these spectra examined only the P waves recorded on short-period vertical instruments (Shearer et al., 2006). We stacked the source spectra within bins of different seismic moment and fit the resulting size-dependent source spectra simultaneously for the theoretical source model of Madariaga (1976) and a single empirical Green's function (EGF) for the complete dataset. We obtained a good fit using an ω^{-2} model and a constant stress drop of $\Delta\sigma = 1.6$ MPa (see Figure 1). The fit is not significantly improved when the stress drop is allowed to vary as a function of moment or when different high-frequency falloffs are applied.

These results show that the average stress drop of small earthquakes in southern California has no significant dependence on seismic moment, confirming the earlier results of Prieto et al. (2004) on a more restricted dataset. This suggests that the earthquakes obey self-similarity, at least over the $M = 1 - 3.4$ range of our observations. Another check on our method is obtained by fitting the distance dependent spectral terms with a constant P -wave Q model. Here we find a good fit is achieved using $Q = 560$, in reasonable agreement with results of Schlöterbeck and Abers (2001).

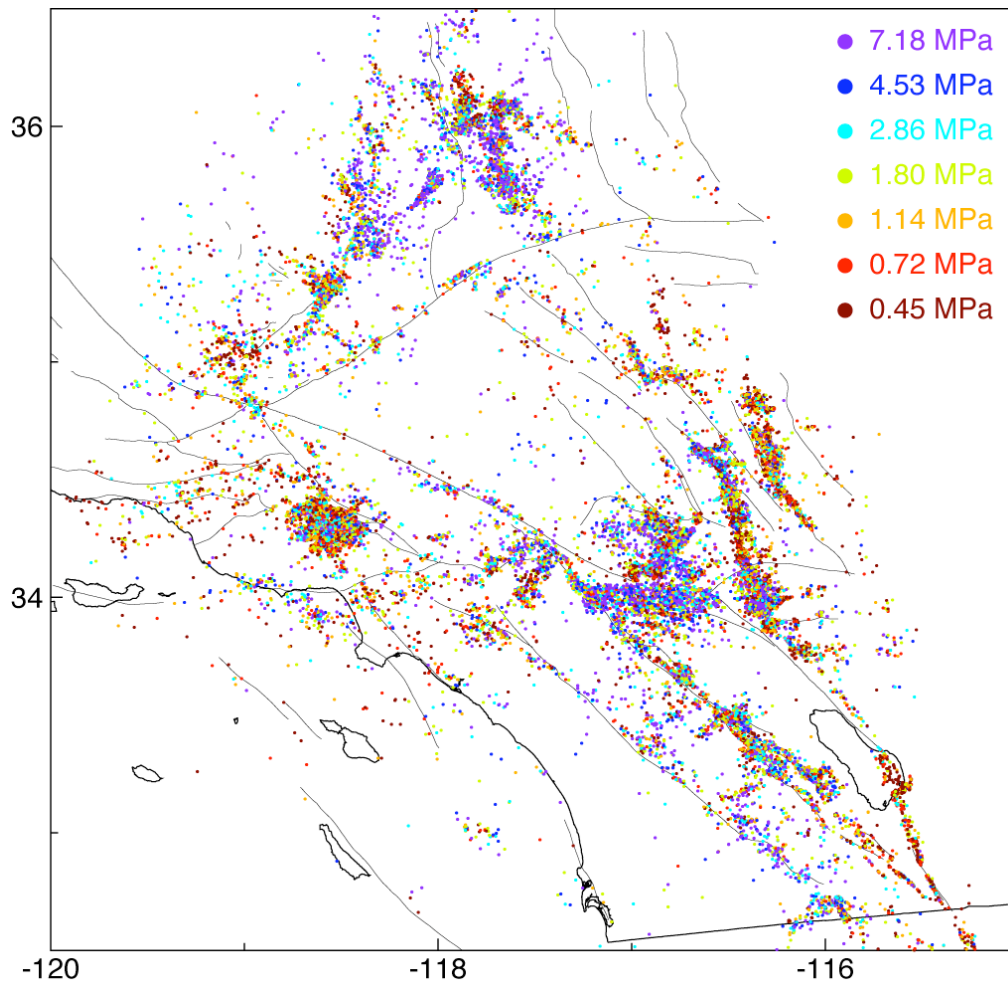


Figure 2. Estimated stress drops for over 65,000 southern California earthquakes from 1989 to 2001. Red indicates stress drops less than the median value of 1.6 MPa, blue indicates higher than average stress drops. Symbol size is proportional to the log deviation from 1.6 MPa.

Next, we adapted our EGF method to correct each source spectrum for the response of 500 neighboring earthquakes. In principle, this will correct for any near-source attenuation differences that could be biasing results between different regions (i.e., Q variations that deviate from the average value for all of southern California obtained with our stacking approach). Individual event stress drops as obtained by fitting each EGF corrected source spectrum using the Aberbrombie (1995) model are plotted in Figure 2. Lower than average $\Delta\sigma$ values (reduced high frequencies) are plotted in red and higher than average $\Delta\sigma$ values (increased high frequencies) are plotted in blue. These source terms exhibit spatially coherent patterns. For example, Northridge aftershocks and events in the Imperial Valley are relatively depleted in high frequencies, indicating either lower than average stress drops or slow rupture velocities (we assume constant rupture velocity for comparison purposes). In contrast, apparently high average stress drops are seen in the Big Bear region.

Individual event stress drops exhibit considerable scatter, with values ranging from 0.2 to 20 MPa. This scatter is not significantly reduced when more records are required for each event stack, indicating that this variation is a real feature and not simply a measure of noise in our estimation methods. Spatial variations in average stress drop are less, but nonetheless range from 0.5 MPa for earthquakes at the southern end of the Salton Sea to 4 MPa at the northern end of the San Jacinto fault.

These results for southern California are described in Shearer et al. (2006) and application of a similar method to data from the Parkfield region of the San Andreas fault are described in Allmann and Shearer (2007). At Parkfield we obtain stress-drop estimates that vary from 0.1 to over 100 MPa with a median value of 6.75 MPa, significantly higher than we observed across most of southern California. The estimated median stress drops show significant lateral variations; we found lower stress drops near the Middle Mountain asperity and along the creeping fault section, and higher stress drops in the hypocentroidal region of the 2004 M6.0 Parkfield earthquake. Comparing stress drops before and after the mainshock, we found that the pattern of high- and low-stress-drop regions is largely unaltered by the earthquake. However, we were able to identify some statistically significant increases in stress drop, most clearly in the vicinity of the 1966 mainshock and along the creeping fault section. In addition, we observed generally increased t^* values following the 2004 mainshock, indicating increased attenuation, particularly in the area between the 1966 and 2004 hypocenters.

We have made less progress during the last year. We spent considerable time experimenting with computing and analyzing S spectra, using three-component TriNet data from 2002 to 2005. Our stacking and processing approach is identical to that used for P -wave spectra in Shearer et al. (2006) and Allmann and Shearer (2007) except that we use the transverse component (i.e., after rotating the horizontal components into transverse and radial). Our goal was to compare P and S corner frequencies to see if we could estimate the average f_p to f_s ratio and verify the value of 1.6 obtained by Prieto et al. (2004) and check the theoretical value of 1.5 predicted by the Madariaga (1976) model. This is critical test of theoretical source models and their applicability to real earthquakes. However, we found that the S -wave signal-to-noise was very poor at high frequencies because of contamination from P coda, which prevented reliable observations

of *S*-wave corner frequencies. It appears that borehole data and/or coda methods will be needed to address this problem.

We made more progress on a related project, which involved comparing the spectra of earthquakes and quarry blasts in southern California. A constant stress drop model gives a good fit to the observed average earthquake spectra over a wide range of moment, but provides a mediocre fit to the average quarry blast spectra, which have a generally steeper falloff at high frequencies than the earthquakes. We also compare *P* and *S*-wave amplitudes and find modestly smaller average *S* amplitudes for the explosions compared to the earthquakes. For southern California, the RMS misfit of *P*-wave spectra to the source model is a more reliable explosion discriminant than the *S*-to-*P* amplitude ratio and works for about 90% of the events. Results of this study are described in Allmann et al. (2008).

References

- Abercrombie, R.E., Earthquake source scaling relationships from -1 to 5 ML using seismograms recorded at 2.5-km depth, *J. Geophys. Res.*, **100**, 24,015-24,036, 1995.
- Allmann, B.P., and P.M. Shearer, Spatial and temporal stress drop variations in small earthquakes near Parkfield, California, *J. Geophys. Res.*, **112**, B4, B04305, doi:10.1029/2006JB004395, 2007.
- Allmann, B.P., P. M. Shearer, and E. Hauksson, Spectral discrimination between quarry blasts and earthquakes in southern California, *Bull. Seismol. Soc. Am.*, **98**, 2073–2079, doi: 10.1785/0120070215, 2008.
- Madariaga, R., Dynamics of an expanding circular fault, *Bull. Seismol. Soc. Am.*, **66**, 639–666, 1976.
- Prieto, G., P.M. Shearer, F.L. Vernon and D. Kilb, Earthquake source scaling and self-similarity estimation from stacking *P* and *S* spectra, *J. Geophys. Res.*, 109, B08310, doi:10.1029/2004JB003084, 2004.
- Schlotterbeck, B.A. and G.A. Abers, Three-dimensional attenuation variations in southern California, *J. Geophys. Res.*, **106**, 30,719-30,735, 2001.
- Shearer, P. M., G. A. Prieto, and E. Hauksson, Comprehensive analysis of earthquake source spectra in southern California, *J. Geophys. Res.*, 111, B06303, doi:10.1029/2005JB003979, 2006.

Non-technical Summary

Seismic wave spectra provide valuable information about earthquake source properties and the attenuation structure of the southern California crust. We systematically compute compressional and shear-wave spectra from over 300,000 southern Californian earthquakes and analyze them to separate source and propagation path effects.

Reports Published

Shearer, P. M., G. A. Prieto, and E. Hauksson, Comprehensive analysis of earthquake source spectra in southern California, *J. Geophys. Res.*, **111**, B06303, doi:10.1029/2005JB003979, 2006.

Allmann, B.P., and P.M. Shearer, Spatial and temporal stress drop variations in small earthquakes near Parkfield, California, *J. Geophys. Res.*, **112**, B4, B04305, doi:10.1029/2006JB004395, 2007.

Allmann, B.P., P. M. Shearer, and E. Hauksson, Spectral discrimination between quarry blasts and earthquakes in southern California, *Bull. Seismol. Soc. Am.*, **98**, 2073–2079, doi: 10.1785/0120070215, 2008.